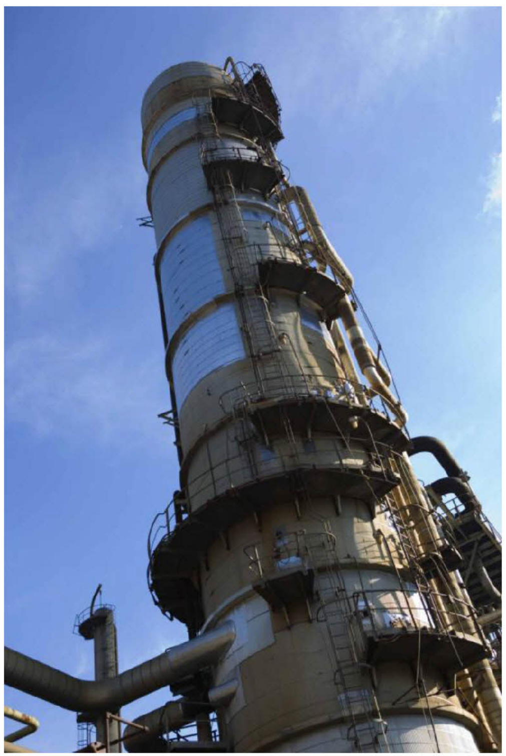
Materials and Code Basics

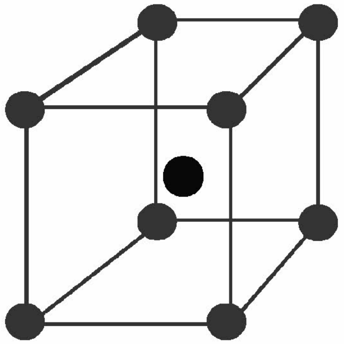


Senior Analyst and Inspector Training
Crude Units

Nature of Metals

- Metals behavior is largely determined by its:
  - Crystal structure and phase
  - Chemical composition
- The crystal structure refers to the highly ordered way the major atoms of the steel are arranged

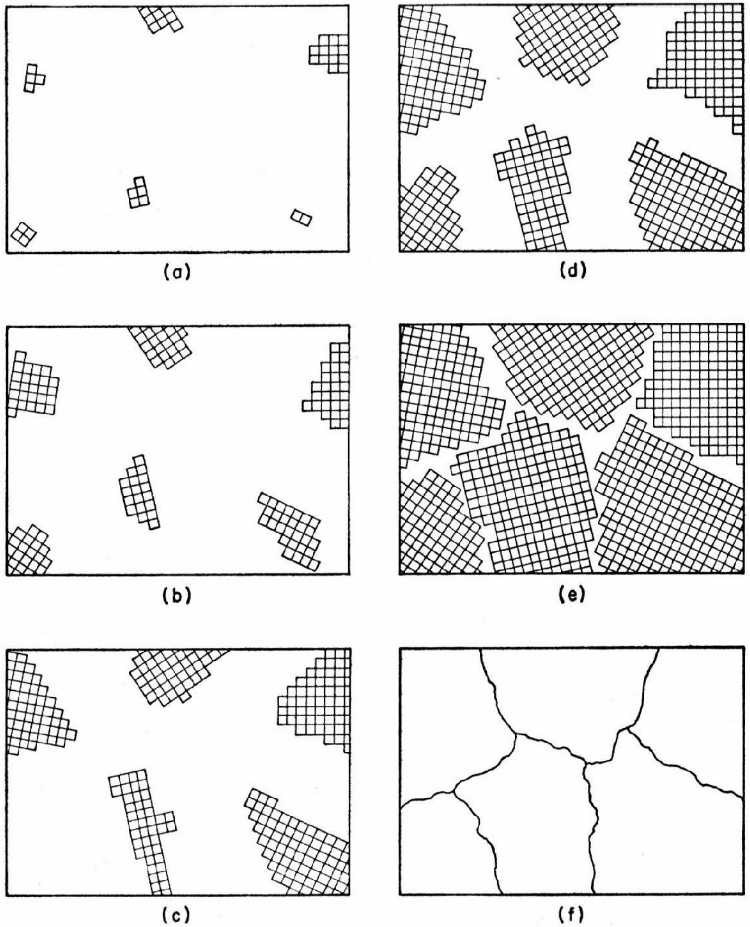
  Example: Steel at room temperature has the iron atoms arranged in the "body centered cubic" crystal structure (called "ferrite")



Nature of Metals

- Most metals used in refining are actually alloys, and contain more than one element
  - "Carbon steel" is an alloy of iron, carbon, and usually manganese and silicon
  - "Low alloy steel" usually contains 1-9% Cr, Ni, Mo, or other elements to improve the strength, toughness, or other properties
- Most metals we use involve more than one phase
  - Iron carbides in steel provide strength
  - Sulfide or oxide inclusions create weak spots for mechanical or hydrogen damage

Formation of Grains and Grain Boundaries in Metals



Ferrite-Pearlite Microstructure of Carbon Steel

- White: Ferrite
- Black: Iron-Carbide
- Laminar areas of mixed Ferrite & Iron-Carbide is called Pearlite

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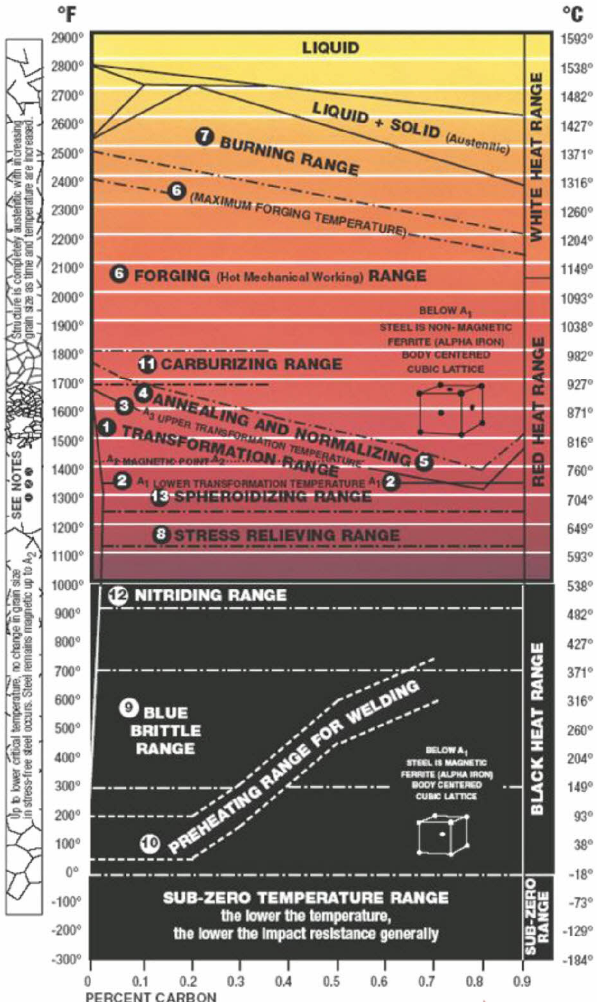
Basic Guide to Ferrous Metallurgy



1. **TRANSFORMATION RANGE-** In this range steels undergo internal atomic changes which radically affect the properties of the material.
2. **LOWER TRANSFORMATION TEMPERATURE (A_1).** Termed Ac_1 on heating, Ar_1 on cooling. Below Ac_1 structure ordinarily consists of FERRITE and PEARLITE (see below). On heating through Ac_1 these constituents begin to dissolve in each other to form AUSTENITE (see below) which is non-magnetic. This dissolving action continues on heating through the TRANSFORMATION RANGE until the solid solution is complete at the upper transformation temperature.
3. **UPPER TRANSFORMATION TEMPERATURE (A_3).** Termed Ac_3 on heating, Ar_3 on cooling. Above this temperature the structure consists wholly of AUSTENITE which coarsens with increasing time and temperature. Upper transformation temperature is lowered as carbon increases to 0.85% (eutectoid point).

- **FERRITE** is practically pure iron (in plain carbon steels) existing below the lower transformation temperature. It is magnetic and has very slight solid solubility for carbon.
- **PEARLITE** is a mechanical mixture of FERRITE and CEMENTITE.
- **CEMENTITE** or IRON CARBIDE is a compound of iron and carbide, Fe_3C.
- **AUSTENITE** is the non-magnetic form of iron and has the power to dissolve carbon and alloying elements.

4. **ANNEALING,** frequently referred to as FULL ANNEALING, consists of heating steels to slightly above Ac_3, holding for AUSTENITE to form, then slowly cooling in order to produce small grain size, softness, good ductility and other desirable properties. On cooling slowly the AUSTENITE transforms to FERRITE and PEARLITE.
5. **NORMALIZING** consists of heating steels to slightly above Ac_3, holding for AUSTENITE to form, then followed by cooling (in still air). On cooling, AUSTENITE transforms giving somewhat higher strength and hardness and slightly less ductility than in annealing.
6. **FORGING RANGE** extends to several hundred degrees above the UPPER TRANSFORMATION TEMPERATURE.
7. **BURNING RANGE** is above the FORGING RANGE. Burned steel is ruined and *cannot be cured* except by remelting.
8. **STRESS RELIEVING** consists of heating to a point below the LOWER TRANSFORMATION TEMPERATURE, A_1, holding for a sufficiently long period to relieve locked-up stresses, then slowly cooling. This process is sometimes called PROCESS ANNEALING.
9. **BLUE BRITTLE RANGE** occurs approximately from 300° to 700°F. Peening or working of steels should not be done between these temperatures, since they are more brittle in this range than above or below it.
10. **PREHEATING FOR WELDING** is carried out to prevent crack formation. See TEMPIL° PREHEATING CHART for recommended temperature for various steels and non-ferrous metals.
11. **CARBURIZING** consists of dissolving carbon into surface of steel by heating to above transformation range in presence of carburizing compounds.
12. **NITRIDING** consists of heating certain *special steels* to about 1000°F for long periods in the presence of ammonia gas. Nitrogen is absorbed into the surface to produce extremely hard "skins".
13. **SPHEROIDIZING** consists of heating to just below the lower transformation temperature, A_1, for a sufficient length of time to put the CEMENTITE constituent of PEARLITE into popular form. This produces softness and in many cases good machinability.

- **MARTENSITE** is the hardest of the transformation products of AUSTENITE and is formed only on cooling below a certain temperature known as the M_s temperature (about 400° to 600°F for carbon steels). Cooling to this temperature must be sufficiently rapid to prevent AUSTENITE from transforming to softer constituents at higher temperatures.
- **EUTECTOID STEEL** contains approximately 0.85% carbon.
- **FLAKING** occurs in many alloy steels and is a defect characterized by localized micro-cracking and "flake-like" fracturing. It is usually attributed to hydrogen bursts. Cure consists of cooling to at least 600°F before air-cooling.
- **OPEN OR RIMMING STEEL** has not been completely deoxidized and the ingot solidifies with a sound surface ("rim") and a core portion containing blowholes which are welded in subsequent hot rolling.
- **KILLED STEEL** has been deoxidized at least sufficiently to solidify without appreciable gas evolution.
- **SEMI-KILLED STEEL** has been partially deoxidized to reduce solidification shrinkage in the ingot.
- **A SIMPLE RULE:** Brinell Hardness divided by two, times 1000, equals approximate Tensile Strength in pounds per square inch. (200 Brinell ÷ 2 x 1000 = approx. 100,000 Tensile Strength, p.s.i.).

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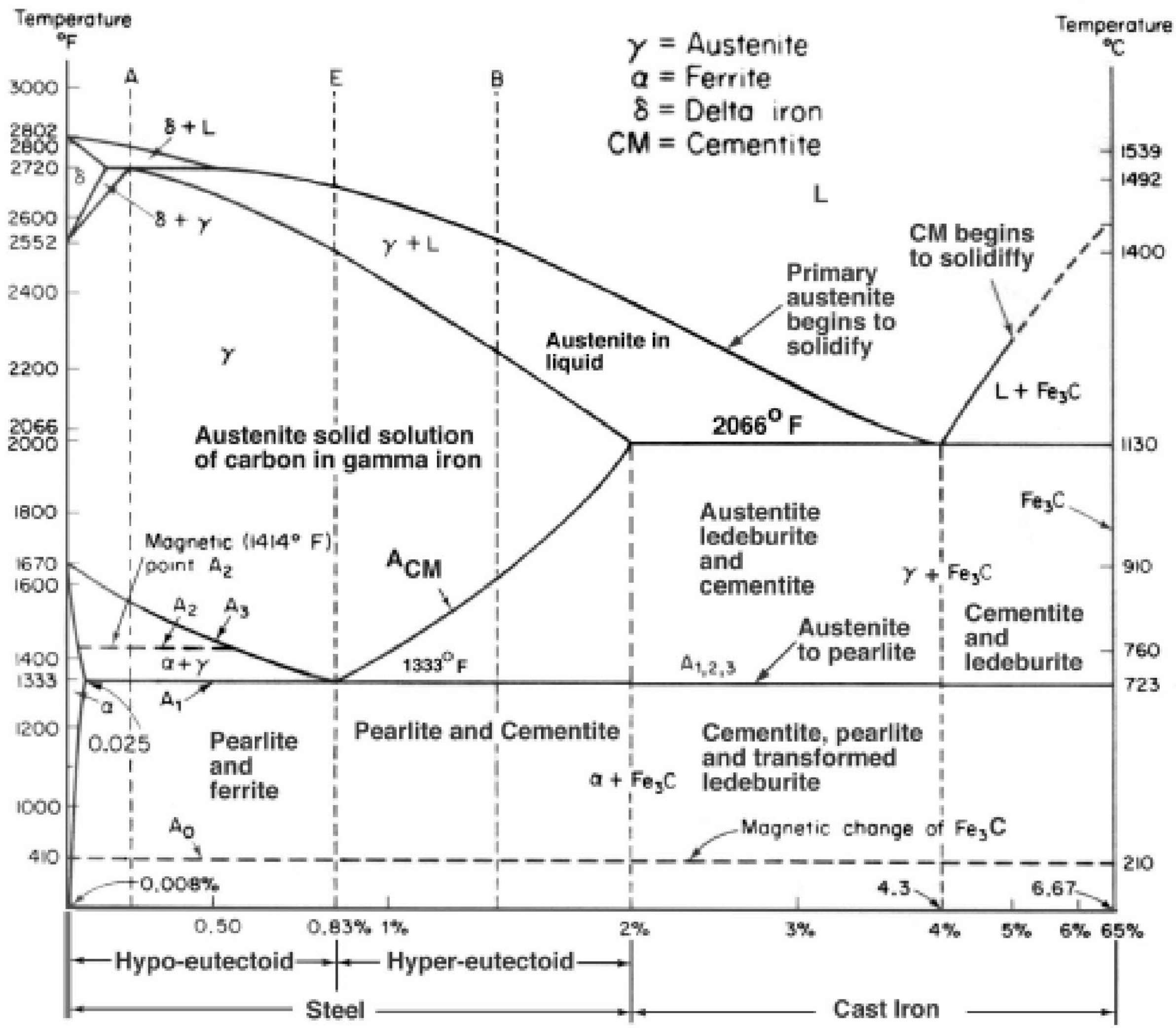
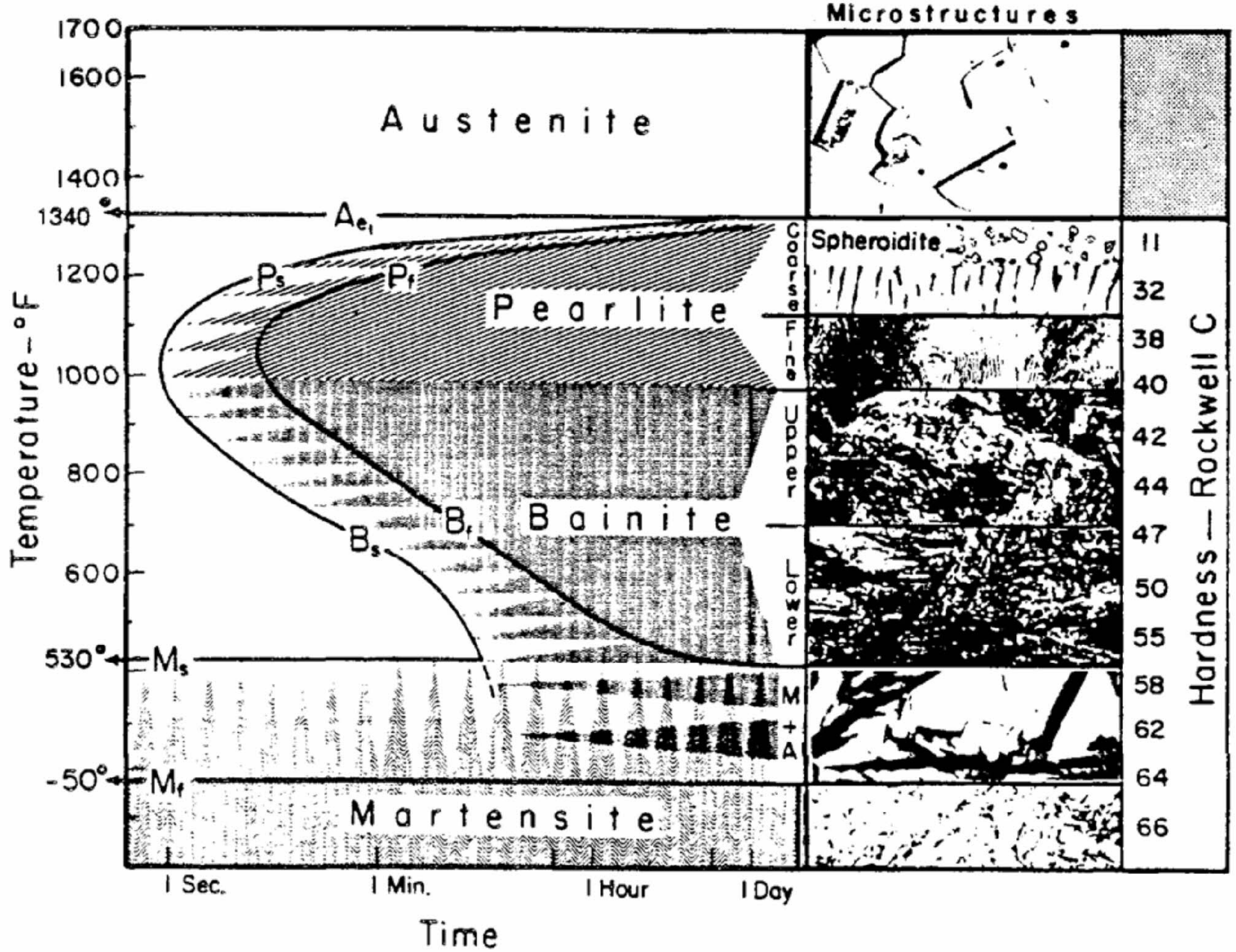
Iron-Carbon Phase Diagram



Time-Temperature-Transformation Diagram



Heat Treatment Terminology

- Carbon and Alloy Steels
  - **Annealing**: Heating a steel to about 1650°F (900°C) so that a single phase develops, with all of the elements dissolved in it, followed by a very slow cool (furnace cool) to prevent hardening. This is the softest and lowest strength state.
  - **Normalizing**: Heating carbon or low alloy steels to about the same temperature as annealing, but cooling fairly rapidly in air. Improves toughness of steels.
  - **Quenching**: Rapidly cooling from annealing temperatures, such as by using oil or water sprays. Results in higher hardness and strength.
  - **Post-Weld Heat Treatment (PWHT)**: Performed after welding to reduce residual stresses and, for ferritic steels, to temper (soften) the weld zone and improve its toughness
  - **Tempering**: Typically done after quenching at temperatures similar to those used for PWHT (e.g., 1300°F/705°C for 2.25 Cr) to relieve the stresses and soften the material)

Heat Treatment Terminology (Cont'd)

- Stainless Steels
  - **Solution Annealing**: Most often our industry uses the term to refer to heat treatment of stainless steels (say, at 2100°F/1150°C) with controlled cooling to provide maximum corrosion resistance
  - **Stabilize Annealing**: Sometimes called thermal stabilization. A heat treatment of some stainless steels to "stabilize" or "lock in" desirable carbides. This allows the SS to be used effectively at high temperatures.

Ferritic Steels: Characteristics

- Includes carbon steels, Cr-Mo alloy steels, and 400 Series stainless steels
- Are magnetic
- Exhibit ductile-to-brittle transition temperature
- Most are “hardenable” by heat treatment or welding
- Post-weld heat treated to relieve stress and reduce hardness
- Immune to chloride SCC
- Susceptible to cracking by wet H_2S, carbonate, amine

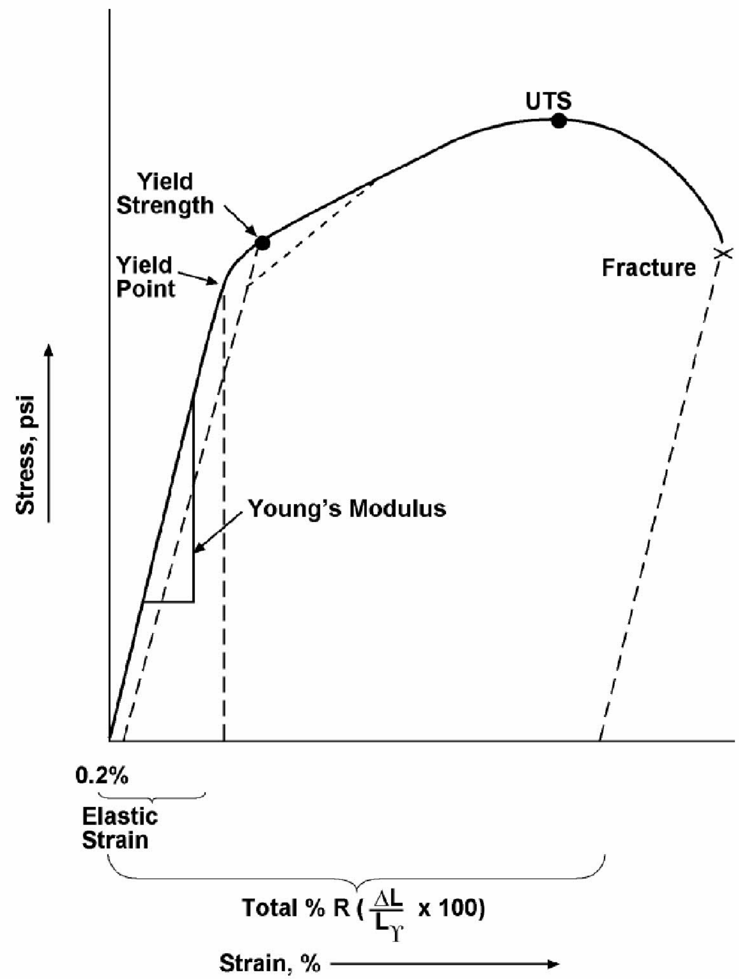
Austenitic Steels: Characteristics

- Includes most 300 Series stainless steels and high Ni steels
- Are non-magnetic, but welds and castings have some magnetism (ferrite)
- No ductile-to-brittle transition; good toughness at low temperature
- Are not hardenable by heat treatment (a few precipitation hardened {PH} SS are exceptions)
- Post-weld heat treated for stress relief, for corrosion resistance, or to soften (especially after cold working)
- Susceptible to chloride SCC
- Resist cracking by wet H_2S, carbonate, amine

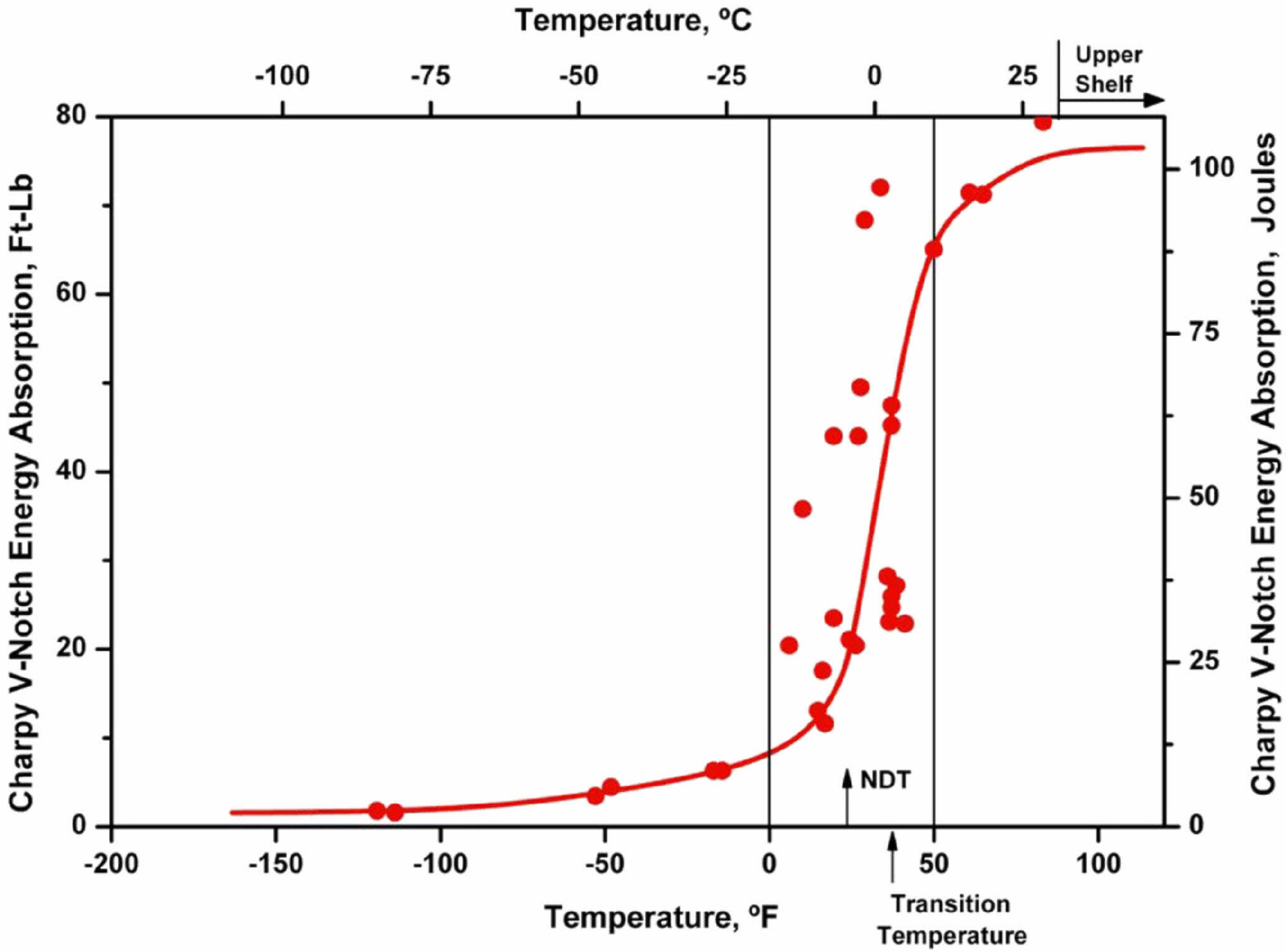
Comparison: C & C-Mn Steel Versus Cr-Mo Steels

Characteristic	C&C-Mn Steels	Cr-Mo Steels
Hardening by Heat Treatment or Welding	Low	High
Preheat for Welding	Heavy Sections Only	Always
PWHT Required	>1-1/2" (38 mm) Thick, or for Environment	"Always," With Few Exceptions
In-Service Embrittlement	No (Rare)	Yes 650-1050°F (345-565°C)
Allowable Stress at 1000°F (540°C)	<3 ksi (21 MPa)	7-10 ksi (48-69 MPa)
Maximum Code Temperature, °F	1000 (540°C) (800°F / 425°C for Graphitization)	1200 (650°C)
H_2 Attack Limit at 750 psia, °F	500 (260°C)	1000 (540°C)

Nominal Stress; Strain Diagram



Charpy V-Notch Energy Absorption of A516 Grade 70 Steel



U.S. Codes Applicable to Various Equipment Items

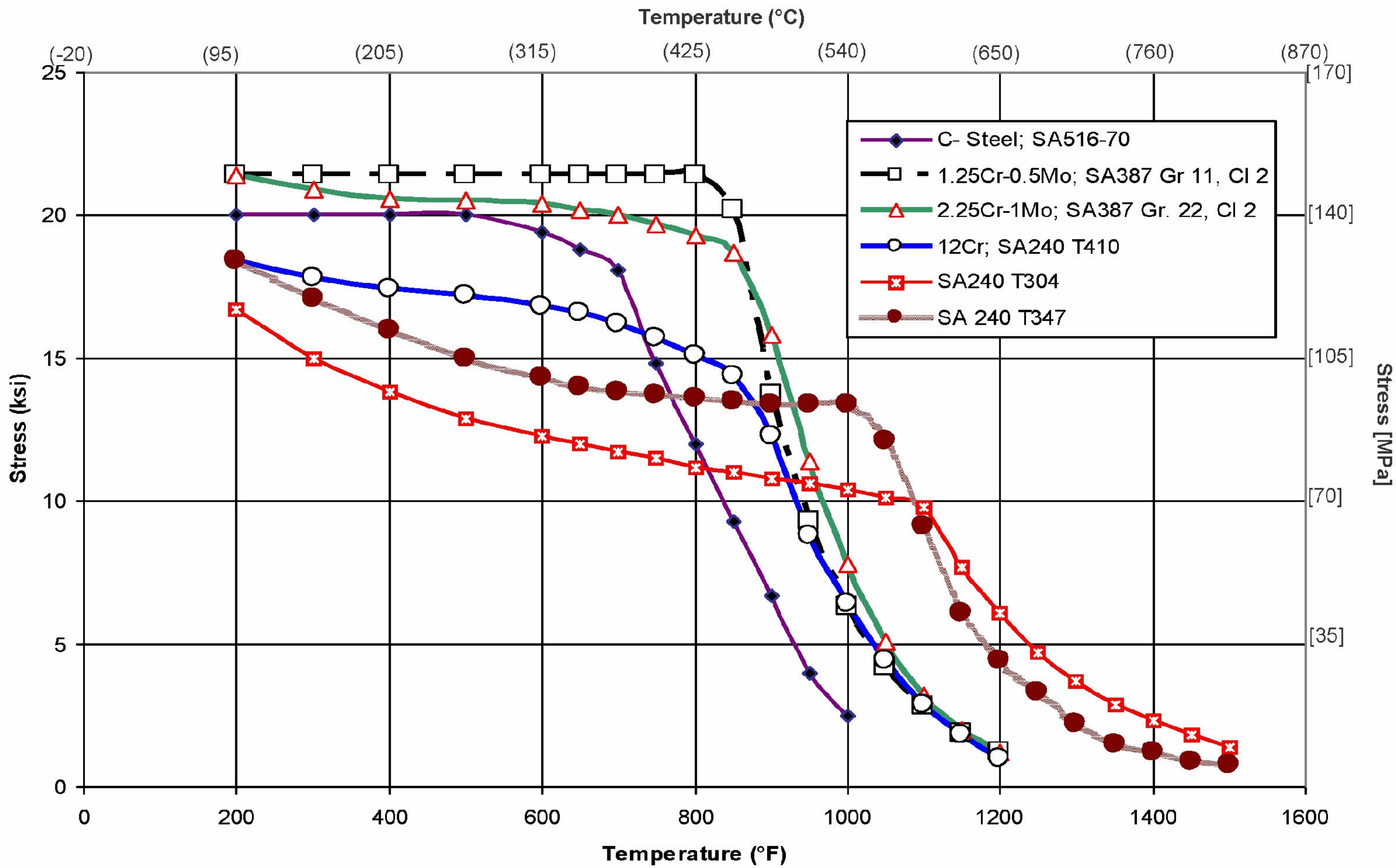
Pressure Vessels	
Design & Fabrication	ASME Section VIII Div. 1; ASME Section VIII Div. 2
Inspection & Repair	NBIC / API 510
Fitness for Service	API RP 579 / ASME FFS-1
Process Piping	
Design & Fabrication	ASME/ANSI B31.3
Inspection & Repair	API 570
Fitness for Service	API RP 579 / ASME FFS-1
Fired Heaters	
Tube Design	API RP 530
Inspection & Repair	API RP 573
Fitness for Service	API RP 579 (Omega)

Basis for Establishing Allowable Stresses for Materials Other Than Bolting

- Allowable stresses are the lowest value obtained from specified percentages of the following properties:

	ASME Section VIII	
Property	Division 1	Division 2
Tensile Strength	28.6 (25 Prior to 1999)	41.7
Yield Strength	66.7	66.7
1% Creep in 100,000 Hours	100 (of Average)	Same
Stress to Rupture in 100,000 Hours	67 (of Average) 80 (of Minimum)	Same Same

Allowable Stresses for Plate Steels
ASME Section VIII Division 1



Material Temperature Limits, °F (°C)

	Carbon Steel	C - 1/2 Mo	1-1/4 Cr - 1/2 Mo	2-1/4 Cr - 1 Mo	5 Cr - 1/2 Mo	12 Cr (410)	18 Cr - 8 Ni (304)	25 Cr - 20 Ni (310)
Strength (3,000 psi) (20,700 kPa)	990 (530)	1075 (580)	1135 (615)	1150 (620)	1115 (600)	1100 (595)	1275 (690)	1320 (715)
Oxidation (10 mpy Loss) (0.25 mmpy)	1050 (565)	1050 (565)	1100 (595)	1175 (635)	1200 (650)	1400 (760)	1500 (815)	2050 (1120)
Graphitization (Welded Only)	800 (425)	850 (555)						
Temper Embrittlement				650-1050 (345-525)				
885 Embrittlement						650-950 (345-510)		
Sigma Embrittlement							1100-1700 (595- 925)	1100-1700 (595- 925)
Hardening on Cooling	1330 (720)	1350 (730)	1375 (745)	1425 (775)	1425 (775)	1450 (790)		
Hydrogen Damage								
(H_2pp, 750 psi) (5,200 kPa)	500 (260)	500 (260)	1000 (540)	1100 (595)	1150 (620)			
(H_2pp, 2000 psi) (13,800 kPa)	460 (240)	460 (240)	650 (345)	850 (555)	1125 (605)			
Caustic Embrittlement Stress Corrosion Cracking	110 (45)	110 (45)	110 (45)	110 (45)	110 (45)	110 (45)	200 (95)	200 (95)
Chloride Stress Corrosion Cracking							140 (60)	140 (60)
Sulfidation (Hot H_2S Corrosion)	500 (260)	500 (260)	500 (260)	500 (260)	650 (345)			
Hot H_2-H_2S Corrosion (0.1 psia H_2S)	500 (260)	500 (260)	500 (260)	500 (260)	500 (260)	750 (340)	950 (510)	950 (510)
Onset of Creep	800 (425)	900 (480)	900 (480)	900 (480)	900 (480)	950 (510)	1100 (595)	1100* (595*)
Sensitization							750-1500	750-1500 (400-815)
Naphthenic Acid Corrosion	350 (175)	350 (175)	350 (175)	350 (175)	350 (175)	350 (175)	350 (175)	350 (175)

*Cast 25 Cr - 20 Ni (HK40) is 1400°F (760°C)

2007 Relative Pricing of Different Alloys
Budget Prices of Tubes in 10,000 Lb Quantities

Size	Material	ASTM	$/100 Ft
0.085	CS wld	SA-214	60.00
0.083	CS smls	SA-179	85.00
0.083	1¼ Cr–½ Mo smls	SA-213 T11	150.00
0.083	5 Cr–½ Mo	SA-213 T5	185.00
0.049	Duplex 22 Cr-5 Ni wld	SA-789 GR2205	249.00
0.065	18 Cr–8 Ni–Ti wld	SA-249 T321	257.00
0.065	Duplex 22 Cr-5 Ni wld	SA-789 GR2205	311.00
0.065	Admiralty smls	SB-111 CA443	350.00
0.049	Duplex 22 Cr-5 Ni smls	SA-789 GR2205	586.00
0.065	Duplex 22 Cr-5 Ni smls	SA-789 GR2205	642.00
0.049	825 wld	SB-704	870.00
0.065	825 wld	SB-704	1252.00
0.049	825 smls	SB-423	1920.00
0.065	825 smls	SB-423	2373.00
0.065	Hastelloy C-276 smls	SB-622 GRC-276	4304.00

Source: Courtesy of Benicia Fabrication & Machine 5/2007

Typical ASTM Specifications for Materials

Material	Plate	Pipe	Tubing	Forgings	Bars	Castings
Cast Iron						A48 A278
Carbon Steel	A285 A515 A516	A53 A106 A671 A672 A691	A161 A179 A210 A214	A105 A181	A575 A576 A663 A675	
Carbon - 1/2 Mo	A204	A335	A161 A209	A182		A217
1 Cr - 1/2 Mo, 1-1/4 Cr - 1/2 Mo, & 2-1/4 Cr - 1 Mo	A387	A335	A213	A182		A217
5 Cr - 1/2 Mo	A387	A335	A213	A182		A217
12 Cr, CA 15	A240		A268	A182	A479	A217
Austenitic Stainless 304, 304L, 316, 316L, 321, 347, 310, CF3, CF3M, CF8, CF8C, CF8M	A240	A312 A358	A213 A249	A182	A479	A351 A744
HK40 & HP Modified						A297
Duplex Stainless 2205	A240	A790	A789	A182	A276	
Super Stainless AL6XN	B688	B675	B676			

Typical ASTM Specifications for Materials

Material	Plate	Pipe	Tubing	Forgings	Bars	Castings
Incoloy Alloy 800	B409	B407	B407		B408	
Incoloy Alloy 825	B424	B423	B163		B425	
904L	B625	B673 B677	B674 B677		B649	
Alloy 20	B463	B464	B468	B462	B472	A351
Copper	B152	B42	B75 B111			
Admiralty Brass			B111 (Grades B, C, D)			
Naval Brass	B171				B124	
70-30 Cu-Ni	B171	B467 B608	B111 B395			
Titanium	B265	B337	B338	B381	B348	B367
Monel	B127	B165	B163		B164	
Inconel 625	B443	B444	B444	B446		
Hastelloy C276	B575	B622	B622	B574		A494
Ni Resist						A436
Aluminum	B209	B241	B234	B247	B211	

Chromium Steels – Typical Chemistry and Strength

Material	Grade/ Class	Chemistry										Tensile Strength, ksi [MPa]	Yield Strength, ksi [MPa]
		C	Mn	Cr	Mo	Ni	V	Cu	N	Ti	B		
AISI	4140	0.4	0.9	1.0	0.2							90-200 [620-1380]	60-175 [415-1205]
AISI	4340	0.4	0.7	0.8	0.2	1.8						110-220 [760-1515]	100-200 [690-1380]
SA387*	12	0.15	0.5	1.0	0.5							55 (65) [380 (450)]	33 (40) [230 (275)]
SA387*	11	0.15	0.5	1.2	0.5							60 (75) [415 (515)]	35 (45) [240 (310)]
SA387*	22	0.12	0.5	2.2	1.0							60 (75) [415 (515)]	30 (45) [205 (310)]
SA387*	5	0.15	0.5	5.0	0.5							60 (75) [415 (515)]	30 (45) [205 (310)]
SA387*	9	0.15	0.5	9.0	1.0							60 (75) [415 (515)]	30 (45) [205 (310)]

Note: Balance is Fe in all cases.

* Tensile and yield values listed are minimum for Class 1 plate. Values in parenthesis are for Class 2 plate.

Ferritic, Martensitic, and Duplex Stainless Steels – Typical Chemistry and Strength

Common Name (UNS Number)	Cr	Ni	Mo	N	C	Other	Tensile Strength, ksi (MPa)	Yield Strength, ksi (MPa)
410[1] (S41000)	12	0.75			0.15		70 (480)	35 (250)
410S[1] (S41008)	12	0.75			0.08		60 (415)	30 (200)
405[2] (S40500)	13	0.6			0.08	0.2 Al	60 (415)	25 (175)
430[2] (S43000)	17				0.1		65 (450)	30 (200)
440A[1] (S44002)	17		0.6		0.7		105 (725)	60 (415)
2205[3] (S32205)	22	5.5	3.0	0.14	0.02		90 (626)	65 (450)

Notes:
1. Martensitic
2. Ferritic
3. Duplex

Austenitic Stainless Steels – Typical Chemistry

Common Name (UNS Number)	Cr	Ni	Mo	Cu	N	C	Other
304L (S30403)	18	8				0.035	
316L (S31603)	17	11	2.1			0.035	
317L (S31703)	19	13	3.1			0.035	
321 (S32100)	18	11				0.08	Ti = 5 x (C + N) (0.70% Max.)
347 (S34700)	18	11				0.08	Cb + Ta = 10 x C (1.1% Max.)
HK-40	26	20				0.40	
HP Mod.	26	35				0.40	1.2 Cb
310 (S31000)	25	20				0.25	
Alloy 20 Cb3 (N08020)	20	33	2.1	3.5		0.07	Cb = 8 x C (1.0 Max.)
AL-6XN (N08376)	20.5	24	6.2		0.2	0.02	
309 (S30900)	23	13				0.20	

Note: Balance is Fe in all cases.

Common Precipitation Hardening Stainless Steels – Typical Chemistry and Strength

Common Name (UNS Number)	Chemistry						Tensile Strength, ksi (MPa)	Yield Strength, ksi (MPa)
	C	Cr	Ni	Mo	Cu	Other		
17-4PH (S17400)	0.05	16.5	4		4	0.4 Al	150[1] (1030)	135[1] (930)
17-7PH (S17700)	0.06	17	7			1.2 Al	175[2] (1200)	155[2] (1070)
ASTM Grade 660[3] (S66286)	0.04	15	25.5	1.2		2.1 Ti 0.006 B 0.25 V	140 (965)	95 (650)

<u>Notes</u>:

1. Precipitation Hardening Temperature: H 1100°F (400°C)
2. Precipitation Hardening Temperature: H 1050°F (565°C)
3. ASTM A 453 for Bolting, A638 for Forging

High Nickel Alloys – Typical Chemistry and Strength

Common Name (UNS Number)	Cr	Ni	Mo	Cu	C	Other	Tensile Strength, ksi[1] (MPa)	Yield Strength, ksi[1] (MPa)
Monel 400 (N04400)	–	66		31	0.1		70 (480)	25 (170)
Incoloy 800 (N08800)	21	32.5			0.05	0.4 Ti 0.4 Al	65 (450)	25 (170)
Incoloy 825 (N08825)	21	42	3	2.3	0.03	1 Ti	85 (590)	35 (240)
Inconel 600 (N06600)	15.5	76			0.08	8 Fe	80 (550)	30 (200)
Inconel 625 (N06625)	21.5	61	9		0.05	3.7 Cb 4 Fe	120 (830)	60 (415)
Hastelloy C-276 (N10276)	15.5	57	15.5		0.005	4 W 5.5 Fe	115 (800)	52 (560)

Note:
1. Annealed condition.

Copper Alloys – Typical Chemistry and Strength

Common Name (UNS Number)	Chemistry					Tensile Strength, ksi (MPa)	Yield Strength, ksi (MPa)
	Cu	Zn	Sn	Al	Other		
Admiralty Brass (C44300)	70	29	1		0.05 As	48 (330)	18 (125)
Naval Brass (C46400)	60	39	0.7			58 (400)	25 (170)
90-10 Cu-Ni (C70600)	83				1.5 Fe 10 Ni	44 (300)	16 (110)
70-30 Cu-Ni (C71500)	69				0.7 Fe 30 Ni	54 (375)	20 (140)
Aluminum Bronze (C61400)	90			7	3 Fe	76 (525)	33 (230)
Copper (C11000)	99.9					32 (220)	10 (70)